Strojniški vestnik - Journal of Mechanical Engineering 54(2008)12, 830-840
UDC 536.24:699.86
Paper received: 30.06.2008
Paper accepted: 25.09.2008

Multiple Parametric Models of Heat Transfer in Lightweight Building Elements with Ventilated Cavities

Uroš Leskovšek[1,*] - Ciril Arkar[2] - Boštjan Černe[1] - Sašo Medved[2]
[1] Trimo d.d., Trebnje, Slovenia
[2] University of Ljubljana, Faculty of Mechanical Engineering, Slovenia

Lightweight building elements (LBEs) with one or two ventilated cavities are multifunctional building-envelope elements that lower the heat transfer to the ambient and enable solar heating. In the case of two ventilated cavities they operate as recuperative heat exchangers in the building's ventilation system. This paper presents the development of a calculation procedure for the characterisation of such innovative building-envelope elements. Using a commercial numerical tool, a wide range of influential parameters was studied. Based on the numerical results, multiple parametrical models (MPMs) for determining an effective U-value and the heat gains on the supply of ventilation air were developed for the case of an LBE with one ventilated cavity, meanwhile MPMs for calculating the effective U-value and the heat-recovery rate were developed for an LBE with two ventilated cavities. Such MPMs can be integrated into well-known computer tools for buildings' energy-efficiency simulations, for example, TRNSYS. The accuracy of the models was verified with field experiments.

Keywords: lightweight building elements, heat transfer, solar heating, multiple regression

0 INTRODUCTION

Lightweight building elements (LBEs) are frequently used in the construction of shopping centres, sports halls and residential buildings. The distinctive properties of such building elements are a high thermal resistance and a low material mass. As a consequence the dynamic changes in the environment can significantly influence the indoor conditions. These disadvantages of LBEs could be reduced by adding ventilated cavities. Such a building envelope decreases the heat flow through the building envelopment, enhances the thermal stability and enables the utilization of solar energy. Since new regulations about the energy efficiency of buildings [1] will allow the integration of advanced building elements into the buildings' efficiency analyses, calculation models need to be developed for such innovative LBEs.

Several studies on the heat transfer within a ventilated cavity have already been made and presented. S. Maneewan et al. [2], for example, made an analysis of the heat-flow decrease due to roof ventilation in the case of a roof without any thermal insulation. They determined a 16 to 60% reduction in the heat gains on the hottest day in the year. Campi et al. [3] developed a sol-air-temperature-based analytical method for the evaluation of the energy performance achievable with a one-cavity ventilated façade. Campi et al. [4] also analyzed the heat transfer in turbulent and laminar flow regimes in ventilated roofs. G. Y. Yun et al. [5] investigated the heating and cooling energy-demand reduction in buildings with the application of a ventilated façade and the electrical energy output of PV modules mounted on the ventilated façade. D. Infield et al. [6] studied the overall heat-transfer coefficient and the solar gains in partially transparent ventilated PV façades. They performed a monthly energy analysis for two existing buildings. M. Coussirat et al. [7] studied different turbulence and radiation models using the CFD tool and compared the numerical results with measurements made on a ventilated façade. They found the k-ε turbulent model to be the most appropriate. Černe and Medved [8] analyzed the 2D heat-flow amplitude on the inner side of an LBE with one ventilated cavity. They showed that a 2D heat-transfer analysis in long LBEs with a ventilated cavity is necessary for an accurate estimation of the heat-flow amplitude. The same authors [9] numerically investigated the transient heat transfer through an LBE with one ventilated cavity. They developed a Fourier equation to calculate the LBE's performance on a typical summer day. However, building envelope constructions with two ventilated cavities have

*Corr. Author's Address: University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, SI-1000 Ljubljana, Slovenia, uros.leskovsek@fs.uni-lj.si

not been studied in detail so far. In our previous research, Černe and Medved [10], we measured the thermal characteristics of an LBE with two ventilated cavities. We showed that the ventilation and the decrease in the transmission heat loss could be correlated with the sol-air temperature.

No available numerical model for the heat transfer in an LBE with ventilated cavities that can be included in a standardized calculation method, like TRNSYS or in a commercial computer code like TrimoExpert, was found. The aim of this paper is to present the development and verification of multiple parametric models (MPMs) of the heat transfer in a ventilated LBE. The MPMs were formed using the CFD computer code and statistical analyses, and were then verified by field measurements. For an LBE with one ventilated cavity the MPMs for the effective U-value and the supply-air heat gains as a function of ambient temperature, solar radiation, air-flow rate, thickness of the thermal insulation layer and the cavity length were developed. For an LBE with two ventilated cavities, MPMs for heat-recuperation efficiency and the effective U-value were developed as a function of the heat-transfer area between the cavities, the air-flow rate, the ambient temperature, the solar radiation and the thickness of the thermal insulation layer on the inner side of the LBE.

1 FUNCTIONING AND GEOMETRY MODEL OF AN LBE WITH VENTILATED CAVITIES

An LBE with ventilated cavities consists of a standard LBE insulation panel upgraded with one or two additional thin metal sheets that form one or two ventilated cavities. An LBE with one ventilated cavity operates as an unglazed solar air collector during the winter, while the forced ventilation of the cavity leads to a reduction in the heat gains through the LBE in the summer time. A decrease in the heat gains in the summer time can be characterized by the effective heat-transfer coefficient, the so-called effective U-value (U_{eff}). The performance of a solar air collector is measured by the heat flux transferred by the ventilation supply air into the building (q_{air}). In the case of an LBE with two ventilated cavities, fresh supply air flows in the outer cavity and exhaust air from the interior flows in the inner cavity in a counter-flow regime. Such an LBE element can be used as a decentralized ventilation unit or can be connected with a centralized air-conditioning system. In addition, exhaust air thermally activates the core of the LBE, resulting in a reduction of the heat losses. The thermal efficiency of such an element can be characterized by the effective U-value (U_{eff}) and the heat-recovery efficiency of the ventilation (η), which is enhanced by solar radiation during the day time.

To achieve an additional heat-recovery enhancement in an LBE with two ventilated cavities, the heat-transfer area (A) was enlarged with fins of different configurations, in such a way that the heat-transfer area was doubled, tripled or enlarged by five times with respect to the original, plane heat-transfer area (A_0).

In all the analyzed cases the LBE was 1 m wide (w) and had 30-mm-high cavities (h_c). All the metal sheets as well as the fins were made of steel with a thickness of 0.6 mm (δ). The thermal insulation, with a thermal conductivity of 0.04 W/mK (rock wool), had a thickness (d_{ti}) between 0.05 m and 0.25 m. The analyzed LBE configurations are presented in Figure 1.

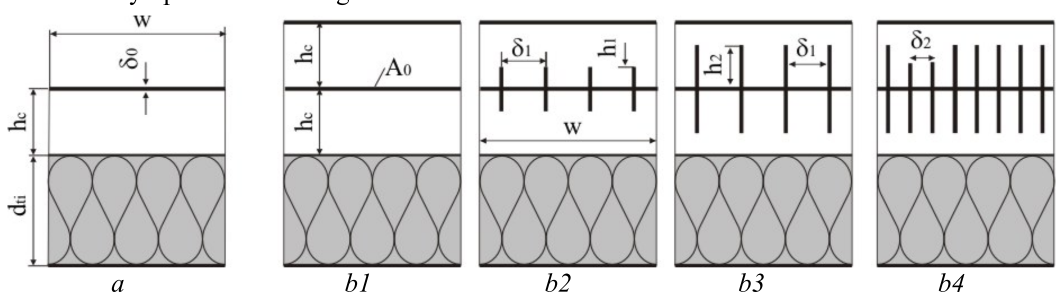


Fig. 1. *a) a cross-section of an LBE with one cavity; b1 to b4) cross-sections of LBEs with two cavities; b1) a=1; b2) a=2 (δ_1=20mm, h_1=10mm); b3) a=3(δ_1=20mm, h_2=20mm); b4) a=5 (δ_2=10mm, h_2=20mm)*

The heat-transfer-area enlargement was achieved by enlarging the fin height (h) and by decreasing the distance between the fins. The ratio between the heat-transfer area (A) and the original plane heat-transfer area (A_0) will subsequently be marked with a.

2 NUMERICAL MODEL OF HEAT TRANSFER IN AN LBE WITH VENTILATED CAVITIES

Using the commercial CFD software PHOENICS [11], a set of Navier-Stokes equations was solved for a 3D model of an LBE with ventilated cavities, applying the finite-volume method. Steady-state numerical simulations were performed since a previous study [12] showed that the heat-accumulation effect could be neglected.

The following boundary conditions were assumed in the numerical models: the outside surface of the LBE exchanges heat with the ambient by convection, by the absorption of solar radiation, and by the exchange of long-wavelength radiation (Figure 2). The value of the absorbed solar radiation (the product of the solar radiation ($G_{glob,\beta}$) and the solar radiation absorptivity (α_s)) varied between 0 and 800 W/m^2. The value of the convective heat-transfer coefficient (α_0) was calculated as a function of the air velocity. The most appropriate empirical relation for calculating the convective heat-transfer coefficient was chosen on the basis of our previous study [13]. The wind velocity was assumed to be 1.2 m/s, which is the average wind velocity in Ljubljana.[14] The sky temperature (T_{sky}) was assumed to be 7 K lower than the ambient temperature, which corresponds with the average sky conditions. The long-wavelength radiation heat transfer between the outside surface of the LBE with ventilated cavities and the sky was set with a linearization of the Stefan–Boltzmann law. In all the studied cases the long-wavelength emissivity of all the cavity surfaces (ε_c) was chosen as 0.9, with regard to the previous optimization of the heat transfer in the cavity [8]. The heat transfer between the inner surface and the indoor environment was described by the convective heat-transfer coefficient (α_i) with a value of 8 W/m^{2}K, as recommended for a building's heat-transfer problems. The indoor air temperature (T_i) was chosen as 20°C, and this was constant in all the studied cases. The length of the LBE (L) was, in the case of one ventilated cavity, 2.4 m, whereas it was 1 m, 2.4 m, 4 m, 8 m and 12 m in the case of the two ventilated cavities.

To obtain the appropriate velocity and temperature fields the k-ε turbulence model [7] was chosen. The long-wavelength radiation within the cavity was calculated with the IMMERSOL [11] radiation model. The air velocity at the inlet in the ventilated cavities was assumed to be uniform across the cross-section.

The boundary conditions were chosen in a range that best fits the meteorological conditions. In the case of an LBE with one ventilated cavity, the influence of the ambient temperature (T_0), the absorbed solar radiation (α_s $G_{glob,\beta}$), the air-flow rate ($\dot{V}$), the thermal insulation thickness (d_{ti}) and the length of the LBE (L) were studied.

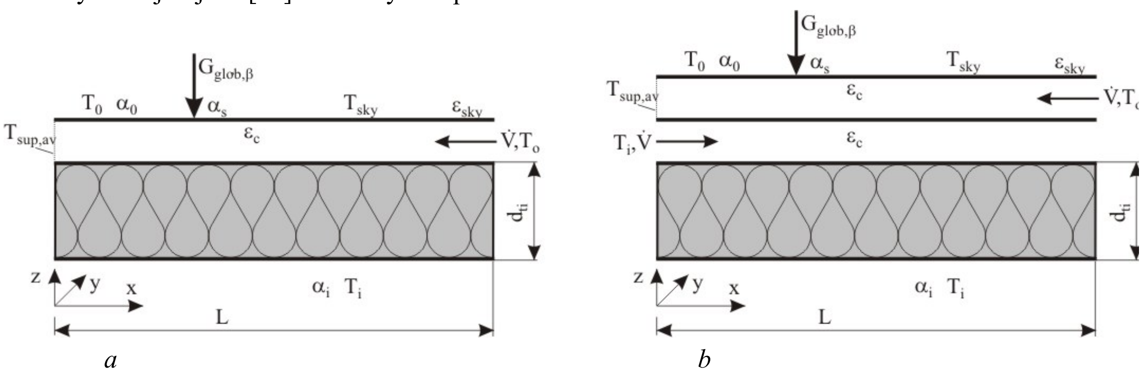


Fig. 2. *Dimensions and boundary conditions in the numerical model;*
a) LBE with one ventilated cavity;
b) LBE with two ventilated cavities cavity

The ambient-temperature boundary condition was varied between -5°C and 20°C, the absorbed solar radiation was varied between 0 and 800 W/m^2, the air-flow rate per 1-m-wide LBE was varied between 20 m^3/hm and 120 m^3/hm, the length of the LBE was varied between 1 and 12 m, and the thickness of the insulation layer was varied between 0.05 m and 0.25 m.

In the case of two ventilated cavities the ambient-temperature boundary condition varied between -5 °C and 17 °C, the absorbed solar radiation varied between 0 and 800 W/m^2, the air-flow rate per 1-m-wide LBE varied between 20 m^3/hm and 80 m^3/hm, and the thickness of the insulation layer varied between 0.05 m and 0.25 m. In addition to the LBE with one ventilated cavity the heat-transfer area was also taken into account. The finned area was up to 5 times enlarged with respect to the original plate heat-transfer area. As the LBE is meant to be integrated into a vertical façade, with a typical floor height of 2.4 m, the length of the element was chosen as 2.4 m.

For a determination of the heat transferred to the supply air, the efficiency of the heat recovery and the effective U-value, the numerically calculated temperature and velocity fields have to be statistically analyzed. The average temperature of the supply air ($T_{sup,av}$) was calculated with respect to the temperatures (T_{sup}) and the air velocities (u_{sup}) at the outlet of the outer cavity:

$$T_{sup,av} = \frac{\iint T_{sup} \cdot u_{sup} \cdot dy \cdot dz}{\iint u_{sup} \cdot dy \cdot dz} \quad (1)$$

The heat gains to the fresh air are proportional to the fresh air's temperature rise. The heat gains were in all cases calculated for a 1-m-wide LBE with one ventilated cavity.

$$\dot{q}_{air} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{sup,av} - T_0) \quad (2)$$

The ratio of the heat recovery in the case of two ventilated cavities was defined as the ratio between the temperature increase of the supply air in the cavity and the difference between the indoor environment and the ambient temperature. Because the supply-air temperature rise is not only a consequence of the heat recovery, but also of the solar radiation, it can be greater than 1.

$$\eta = \frac{T_{sup,av} - T_o}{T_i - T_o} \quad (3)$$

The effective U-value is the ratio between the actual heat flow through the LBE and the difference between the ambient and the indoor temperatures. Because the heat flow through the panel varies significantly in the air-flow direction (x axis), U_{eff} in our case always denotes the average U-value along the whole length of the LBE with ventilated cavities. Because the insulation material is assumed to be homogenous, U_{eff} can be calculated as the average heat flow between two fictive parallel planes in the thermal insulation. If the temperature of one plane is denoted as $T_b(x,y)$, the temperature of another plane as $T_c(x,y)$, the distance between the planes as d and the thermal conductivity of the insulation material as λ_{ti}, then U_{eff} can be calculated as:

$$U_{eff} = \frac{\dot{q}_{LBE}}{T_i - T_0} = \\ = \frac{\frac{\lambda_{ti}}{d} \iint (T_b - T_c) \cdot dx \cdot dy}{\iint dx \cdot dy} \cdot \frac{1}{T_i - T_0} \quad (4)$$

where $U_{eff,o}$ denotes the average effective U-value in the case of an LBE with one ventilated cavity and $U_{eff,d}$ the average effective U-value in the case of an LBE with two ventilated cavities.

3 RESULTS OF THE NUMERICAL EVALUATION VENTILATED CAVITIES

3.1 LBE with one ventilated cavity

The numerical calculations of heat transfer in an LBE with one ventilated cavity show that $U_{eff,o}$ strongly depends on all the analyzed parameters and has a far-from-constant U-value, as predicted in the standardized calculations. The influence of some of the most important parameters on the effective U-value and on the solar gains is presented in Figs. 3 to 6. If not stated otherwise, the simulated air-flow rate ($\dot{V}$) was 40 m^3/h, the thermal insulation thickness (d_{ti}) was 0.1 m, the length of the cavity (L) was 4 m and the ambient temperature (T_0) was 5 °C.

Fig. 3 shows that $U_{eff,o}$ is zero (indicating that the LBE is thermally neutral) in cases when the air-flow rate is up to 60 m^3/h and the absorbed solar radiation is 450 W/m^2, and if the air-flow rate is up to 120 m^3/h and the absorbed solar radiation is close to 800 W/m^2. Positive values of $U_{eff,o}$ represent heat losses to the ambient and

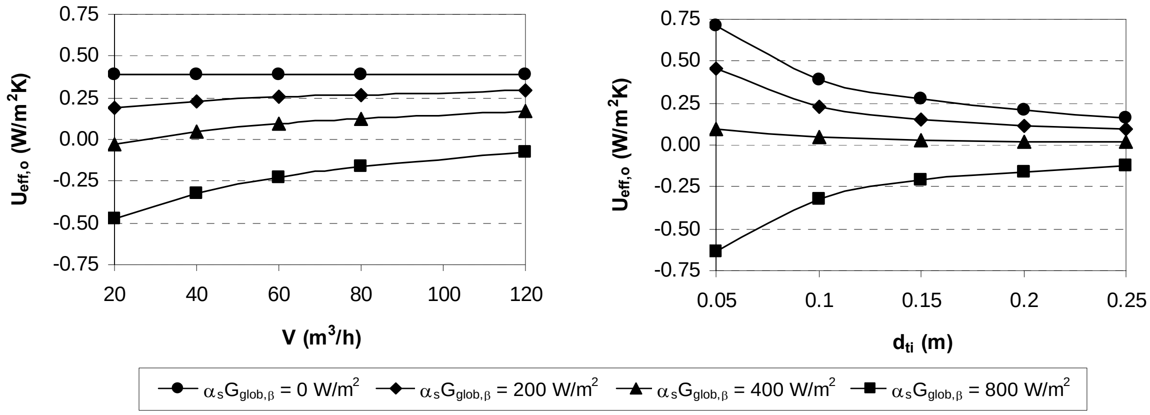


Fig. 3. *The influence of air-flow rate and absorbed solar radiation on* $U_{eff,o.}$*; positive values indicate heat losses and negative heat gains.*

Fig. 4. *The influence of the thickness of the thermal insulation and the absorbed solar radiation on* $U_{eff,o.}$

negative values represent heat gains. Figure 4 shows the changing of the heat-transfer coefficient with the thickness of the thermal insulation. The heat-transfer coefficient decreases with the increasing thickness of the thermal insulation ($U \approx \propto 1/d$). If there is no solar radiation ($G_{glob,\beta}$=0W/m^2), the relationship between $U_{eff,o}$ and d is very similar to the steady-state U-value dependence. The same heat-transfer coefficient as in the case of no solar radiation can be achieved with half of the thermal insulation layer thickness if the absorbed solar radiation is at least 200 W/m^2, and moreover, the $U_{eff,o}$-value can be negative (indicating heat flow towards the interior of the building) if the absorbed solar radiation is above 450 W/m^2.

For the construction of buildings using an LBE with one ventilated cavity, the appropriate length of the ventilated cavity is one of the most important parameters. If the length of the cavity increases, heat gains increase up to a certain cavity length. The active cavity length was, in our case, about 8 m (Figure 5). A further length increase does not influence the heat gains noticeably. Half of the maximum heat gains can be achieved with a length of 1/7 of the maximum LBE length (12 m) if an absorbed solar radiation of 800 W/m^2 and an air-flow rate of 40 m^3/h were taken into account. Figure 6 indicates that variable air-flow-rate operation would be much more efficient than constant air-flow-rate operation because the heat gains are closely related to the solar radiation. The recommended air-flow rate is up to 80 m^3/h if the absorbed solar

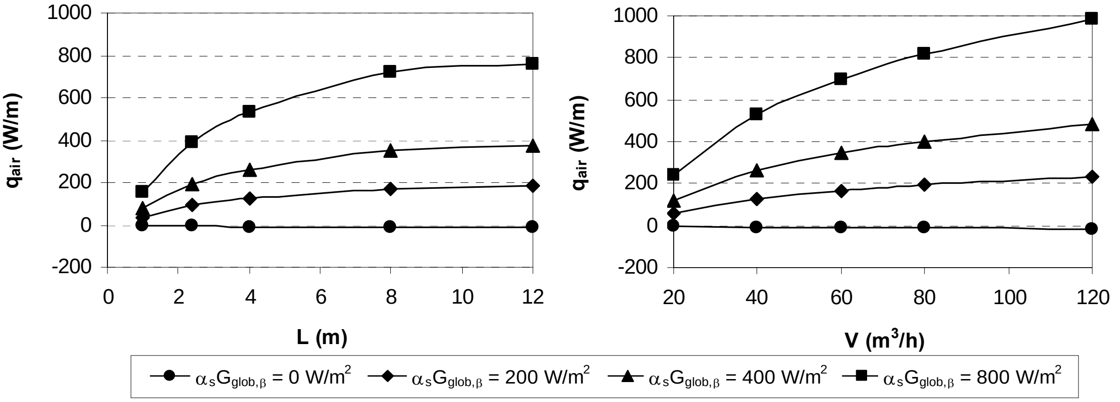


Fig. 5. *The influence of cavity length and absorbed solar radiation on heat gain; positive values indicate heat losses.*

Fig. 6. *The influence of air-flow rate and absorbed solar radiation on heat gains.*

radiation is 200 W/m^2, up to 100 m^3/h if the absorbed solar radiation is 450 W/m^2, whereas a flow rate larger than 120 m^3/h is recommended if the absorbed solar radiation is 800 W/m^2. It should be noted that the indicated parameter values were calculated for selected constant values of the other influential parameters.

3.2 LBE with two ventilated cavities

The numerical modelling of heat transfer in the LBE with two counter-flow ventilated cavities was performed for several configurations, including different cavity-to-cavity heat-transfer areas. The influence of some of the most important parameters on the effective U-value and on the solar gains is presented in Figures 7–10. If not stated otherwise, the air-flow rate ($\dot{V}$) was 40 m^3/h, the thermal insulation thickness (d_{ti}) was 0.1 m, the heat-transfer area (a) was 1 m and the ambient temperature (T_0) was 5 °C.

Figure 7 shows that the thermal activation of the LBE significantly decreases the heat transfer through the LBE with two ventilated cavities. Compared to the original LBE (without ventilated cavities), the standardized U-value is lowered by up to 20 times during the night ($G_{glob,\beta}$= 0 W/m^2). This phenomenon reduces the required thickness of the thermal insulation and reduces the inner-surface condensation risk. Enlargement of the heat-transfer area results in an enhanced heat transfer between the cavities; it enhances the heat recovery from the exhaust air, but also lowers the average temperature difference between both cavities. As a consequence, $U_{eff,d}$ increases with the increased heat-transfer area if the absorbed solar radiation is lower than 200 W/m^2 and decreases if the absorbed solar radiation is higher. The effective U-value changes by up to 4.1 times if the heat-transfer area ratio is 3, and up to 5.2 times if it is 5.

The heat-transfer area is a very important parameter since it is closely related to the recuperation efficiency. The minimum allowed recuperation efficiency is expressed in building-ventilation systems' energy-efficiency regulations. From Figure 9 it is clear that the minimum-allowed recuperation efficiency (η = 0.40) can be achieved without solar radiation if the heat-transfer area ratio (a) is at least 5, but it could be up to 0.8 if the absorbed solar radiation is equal to 200 W/m^2. For the maximum absorbed solar radiation the heat-recovery rate can be as high as 1.8. High efficiency values indicate that such a type of ventilation will importantly contribute to the utilization of solar gains and help to reduce the energy consumption for heating. Figure 10 shows the significance of the air-flow rate and the absorbed solar radiation on the recuperation efficiency. It indicates that the air-flow rate should be regulated with respect to those two parameters to ensure a constant heat-recovery ratio. The air-flow rate should be regulated according to the indoor-air quality criteria. As mentioned before, the presented results correspond to selected constant values of the other influential parameters.

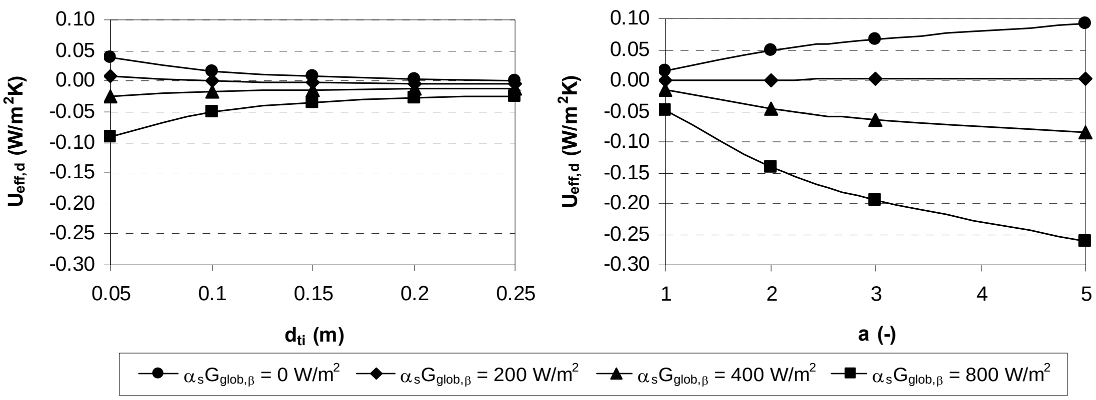


Fig. 7. *The influence of insulation thickness and absorbed solar radiation on* $U_{eff,d}$.

Fig. 8. *The influence of an enlarged heat-transfer area and absorbed solar radiation on* $U_{eff,d}$.

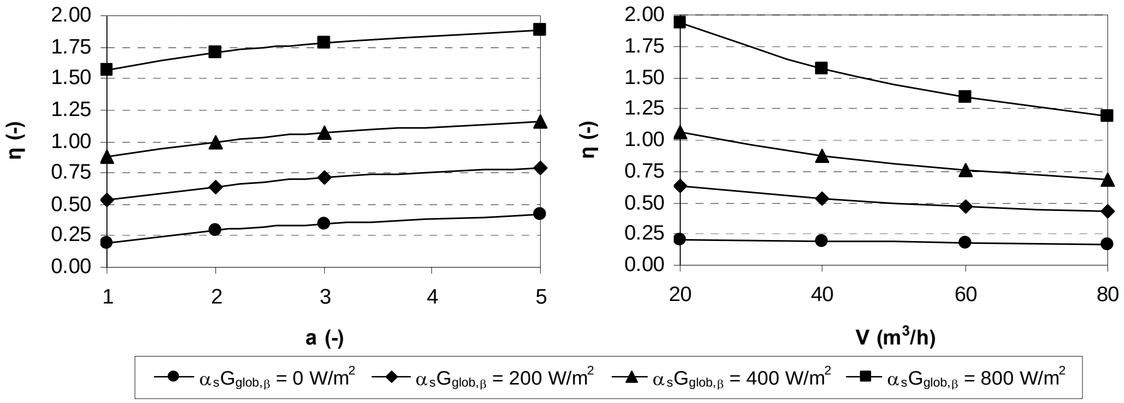


Fig. 9. *The influence of an enlarged heat-transfer area and absorbed solar radiation on the efficiency of heat recovery. (V=40m^3/hm)*

Fig. 10. *The influence of air-flow rate and the absorbed solar radiation on the efficiency of heat recovery. (a=1)*

Figures 8 and 9 indicate that enlarging the heat-transfer area between ventilated cavities enhances heat recovery but reduces the influence of the LBE's thermal activation, although heat gains that appear as a consequence of heat recovery are, for most cases, much bigger than the transmission heat losses through the LBE.

All the presented examples of numerical calculation results show a multiple parametric dependence of the vital thermal characteristics of the LBE with one or two ventilated cavities. The optimization and energy-performance evaluation of such innovative elements are, therefore, enabled only by using the appropriate multiple parametric models. The evaluation of such models will be presented later.

4 MULTIPLE PARAMETRIC MODELS

Multiple regression was used to develop multiple parametric models (MPMs) from the results of numerical modelling. For the LBE with one ventilated cavity about 650 numerical calculations were made, and for the LBE with two ventilated cavities an additional 150 numerical calculations were performed. The regression functions were developed by applying the software Mathematica 6.0 [15]. Different forms of the regression functions were compared with numerically calculated results on the basis of the coefficient of determination (r^2) and the mean square error (MSE). The regression functions with maximum values of r^2 and the minimum of the MSE were assumed to best fit the numerically calculated values.

MPMs are constructed as products of single-parameter regression functions. MPMs for q_{air} and U_{eff} for an LBE with one ventilated cavity and η and U_{eff} for an LBE with two ventilated cavities are presented in Figures 11 to14.

$$U_{eff,o} = h_1(\dot{V}) \cdot h_2(T_0) \cdot h_3(L) \cdot \frac{1}{d_{ti}} + \\ + h_4(\dot{V}) \cdot h_5(T_0) \cdot h_6(L) \cdot \frac{\alpha_s \cdot G_{glob,\beta}}{d_{ti}} \quad (5)$$

where:

$$h_1(\dot{V}) = 5,489 \cdot 10^1 + 3,923 \cdot 10^{-1} \cdot \ln(\dot{V})$$
$$h_2(T_e) = -9,99966 \cdot 10^{-1} + e^{1,41 \cdot 10^{-7} \cdot T_0}$$
$$h_3(L) = 2,135 \cdot 10^1 + 9,134 \cdot 10^{-2} \cdot \ln(L)$$
$$h_4(\dot{V}) = 1,693 \cdot 10^{-2} - 2,419 \cdot 10^{-3} \cdot \ln(\dot{V})$$
$$h_5(T_0) = 1,689 + e^{1,289 \cdot 10^{-1} \cdot T_0}$$
$$h_6(L) = -1,616 \cdot 10^{-3} - 1,131 \cdot 10^{-3} \cdot \ln(L)$$

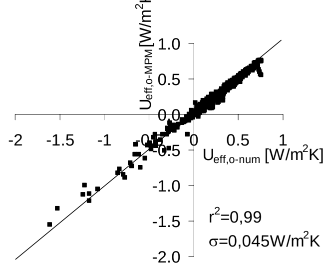


Fig. 11. *MPM for one ventilated cavity $U_{eff,o}$ and single-parameter regression functions; on the right is a comparison between numerically calculated ($U_{eff,0-num}$) and MPM-determined ($U_{eff,0-MPM}$) effective U-values.*

$$q_{air} = f_1(\dot{V}) \cdot f_2(T_0) \cdot f_3(L) \cdot f_4(d_{ti}) \cdot f_5(\alpha_s \cdot G_{glob,\beta}) \quad (6)$$

where are:

$$f_1(\dot{V}) = -1{,}539 + 6{,}387 \cdot 10^{-1} \cdot \ln(\dot{V})$$

$$f_2(T_0) = 1{,}586 - 1{,}066 \cdot 10^{-2} \cdot T_0$$

$$f_3(L) = 7{,}507 \cdot 10^{-1} + 1{,}323 \cdot \ln(L)$$

$$f_4(d_{ti}) = -1{,}678 + 4{,}422 \cdot 10^{-1} \cdot d_{ti}$$

$$f_5(\alpha_s \cdot G_{glob,\beta}) = 1{,}611 - 1{,}273 \cdot 10^{-1} \cdot \alpha_s \cdot G_{glob,\beta}$$

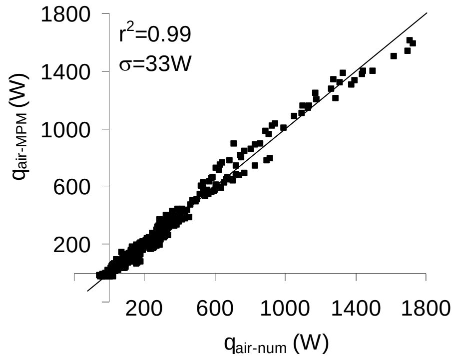


Fig. 12. *MPM for one ventilated cavity q_{air} and single-parameter regression functions; on the right is a comparison between numerically calculated($q_{air-num}$) and MPM-determined ($q_{air-MPM}$) heat gains.*

The LBE with two ventilated cavities operates as a recuperative heat exchanger and a solar air collector. The consequences of this are heat gains on the ventilation air and a reduction of the conductive heat losses through the panel.

$$U_{eff,d} = k_1(\dot{V}) \cdot k_2(T_0) \cdot k_3(a) \cdot \frac{1}{d_{ti}} + \\ + k_4(\dot{V}) \cdot k_5(T_0) \cdot k_6(a) \cdot \frac{\alpha_s \cdot G_{glob,\beta}}{d_{ti}} \quad (7)$$

where:

$$k_1(\dot{V}) = 3{,}818 - 7{,}541 \cdot 10^{-1} \cdot \ln(\dot{V})$$

$$k_2(T_a) = 6{,}949 \cdot 10^{-1} + e^{-1{,}16 \cdot 10^{-2} \cdot T_0}$$

$$k_3(a) = 1{,}409 \cdot 10^{-3} + 2{,}755 \cdot 10^{-3} \cdot \ln(a)$$

$$k_4(\dot{V}) = -4{,}197 \cdot 10^{-4} - 9{,}230 \cdot 10^{-5} \cdot \ln(\dot{V})$$

$$k_5(T_0) = 1{,}041 \cdot 10^{1} + e^{2{,}230 \cdot 10^{-1} \cdot T_0}$$

$$k_6(a) = 3{,}510 \cdot 10^{-3} + 9{,}675 \cdot 10^{-3} \cdot \ln(a)$$

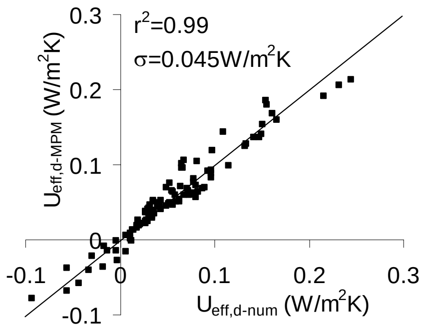


Fig. 13. *MPM for two ventilated cavities $U_{eff,d}$ and single-parameter regression functions; on the right is a comparison between numerically calculated ($U_{eff-num}$) and MPM-determined ($U_{eff-MPM}$) effective U-values.*

$$\eta = g_1(\dot{V}) \cdot g_2(T_0) \cdot g_3(a) + \\ + g_4(\dot{V}) \cdot g_5(T_0) \cdot g_6(a) \cdot \alpha_s \cdot G_{glob,\beta} \quad (8)$$

where:

$$g_1(\dot{V}) = 1{,}143 - 1{,}002 \cdot 10^{-1} \cdot \ln(\dot{V})$$

$$g_2(T_a) = -6{,}742 + e^{4{,}863 \cdot 10^{-2} \cdot T_0}$$

$$g_3(a) = -4{,}382 \cdot 10^{-2} - 3{,}533 \cdot 10^{-2} \cdot \ln(a)$$

$$g_4(\dot{V}) = 2{,}071 \cdot 10^{-3} - 3{,}244 \cdot 10^{-4} \cdot \ln(\dot{V})$$

$$g_5(T_0) = 7{,}310 + e^{2{,}238 \cdot 10^{-1} \cdot T_0}$$

$$g_6(a) = 1{,}901 \cdot 10^{-1} + 7{,}175 \cdot 10^{-3} \cdot \ln(a)$$

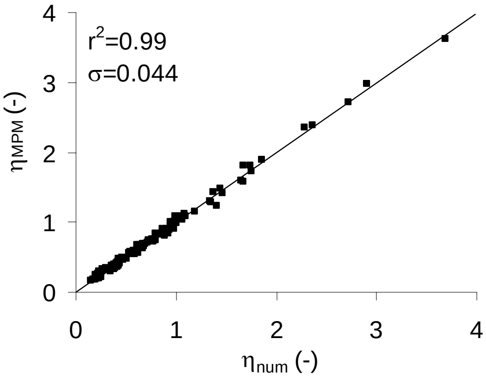


Fig. 14. *MPM for two ventilated cavities η and single-parameter regression functions; on the right is a comparison between numerically calculated (η_{num}) and MPM-determined (η_{MPM}) heat-recovery rates. It was determined that the thickness of the insulation panel does not have a noticeable influence on the heat-recovery rate.*

5 VERIFICATION OF MPMs WITH FIELD EXPERIMENTS

Field experiments were performed to verify the developed MPMs for the calculation of solar gains in the case of an LBE with one ventilated cavity and heat-recuperation efficiency in the case of an LBE with two ventilated cavities. Measurements on the LBE with one ventilated cavity were performed on two test elements (an LBE with a 4-m-long cavity and an LBE with a 2-m-long cavity) in March of 2007. Measurements on the LBE with two ventilated cavities were performed from February until June of 2005. The test element for the two-ventilated-cavities LBE was 3-m high (the length of the cavity was 2.4 m), 1-m wide and the heat-transfer area was not enlarged (a = 1). Indoor conditions were simulated by heating an additional cavity on the inner side of the LBE.

The temperatures in the cavities and the ambient temperature were measured with Ni-CrNi thermocouples. The air velocities were measured with a thermo anemometer and with an orifice plate. Short-wavelength ($G_{glob,\beta}$) and long-wavelength radiation on the top cover of the LBE were measured with a pyranometer and a pyrgeometer, respectively. The wind speed, wind direction and relative humidity of the ambient air were also measured. The measurement data were stored every 5 min using a data logger. For the evaluation of the heat gains the calorimetric method was used. The details of the testing equipment, the measurement results and the error analyses are presented in our earlier publications [10] and [12].

The daily time variation of the solar radiation and the heat gains in the LBE with one ventilated cavity and with two ventilated cavities are presented in Figures 15 and 16, respectively. A comparison of the measurement results and the MPM modelling was performed for a representative sunny and cloudy day.

Comparing the measurement results and the results of the calculation applying the MPM it is clear that only minor differences occur. Because the MPM does not consider heat accumulation, some differences between the measured and calculated values can occur if the solar radiation changes rapidly, which can be easily seen in Figure 15-b. Nevertheless, it does not have a significant influence on the daily performance calculations.

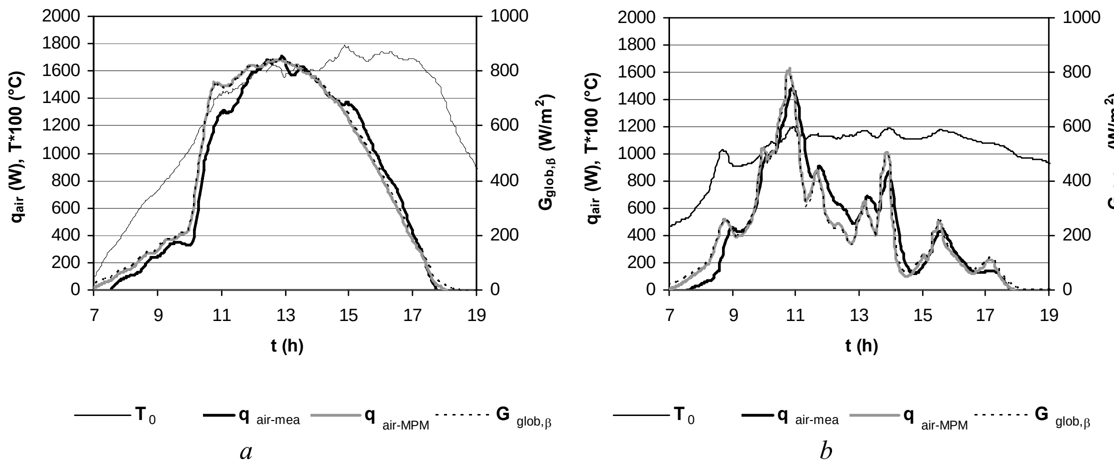
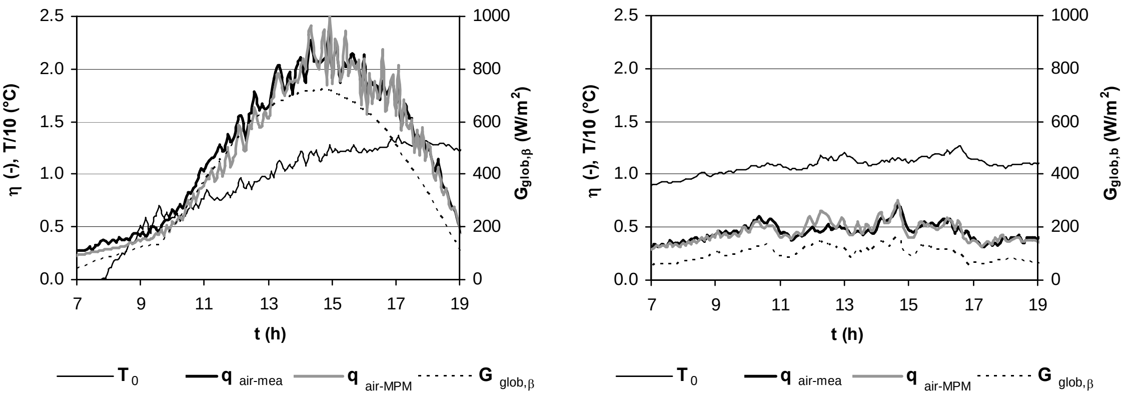


Fig. 15. *Solar radiation, temperature and heat gains in an LBE with one ventilated cavity for a sunny day, 15th March of 2007 (a) and for a cloudy day, 9th March of 2007 (b). The continuous black line marks the measured heat gains, the continuous grey line marks the calculated heat gains using the MPM presented in Section 4. The solar radiation and ambient temperature are marked with dashed lines.*



a *b*

Fig. 16. *Solar radiation, temperature and heat gains in an LBE with two ventilated cavities for a sunny day, 22nd April of 2005 (a) and for a cloudy day, 5th May of 2005 (b). The continuous black line marks the measured heat-recovery rate, and the continuous grey line marks the MPM-calculated heat-recovery rate.*

6 CONCLUSIONS

The heat transfer in two innovative LBEs was analyzed using the CFD approach and MPM analyses. It was shown that such elements improve the energy efficiency of buildings built with LBEs since they act as a thermally activated building envelope, a solar air collector and a heat-recovery unit.

Thermal properties and energy-efficiency indicators were developed in the form of multiple parametric models (MPMs) that enable the computation of a building's energy performance using a well-known simulation code, like TRNSYS, or calculation code, like TrimoExpert. This approach ensures that such elements could be included in buildings' energy-performance calculations according to the Energy Performance of Buildings Directive and used in compulsory feasibility studies regarding to the use of renewable energy sources.

The developed models were verified by field measurements, and we determined that the developed MPMs are satisfactorily accurate.

7 ACKNOWLEDGEMENTS

This study was partly financially supported by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia.

8 REFERENCES

[1] EC, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 On the Energy Performance of Buildings, 2002.

[2] Maneewan S., Hirunlabh J., Khedari J., Zeghmati B., Teekasap S. (2005) Heat gain reduction by means of thermoelectric roof solar collector, *Solar energy* 78, pp. 495-503.

[3] Ciampi M., Leccese F., Tuoni G. (2003) Ventilated façades energy performance in summer cooling of buildings, *Solar energy* 75, pp. 491-502.

[4] Ciampi M., Leccese F., Tuoni G. (2005) Energy analysis of ventilated and micro-ventilated roofs, *Solar energy* 79, pp. 183 - 192.

[5] Yun G. Y., McEvoy M., Steemers K. (2007) Design and overall energy performance of a ventilated photovoltaic façade, *Solar energy* 81, pp. 383-394.

[6] Infield D., Eicker U., Fux V., Mei L., Schumacher J. (2006) A simplified approach to thermal performance calculation for building integrated mechanically integrated PV façades, *Building and environment* 41, pp. 893-901.

[7] Coussirat M., Guardo A., Jou E., Egusquiza E., Cuerva E., Alavedra P. (2008) Performance and influence of numeridal sub-

models on the CFD simulation of free and forced convection in double-glazed ventilated façades, *Energy and Buildings* 40, pp. 1781-1789.

[8] Černe B., Medved S. (2005) The dynamic thermal characteristics of light weight building elements with a forced ventilation cavity and radiation barriers, *Energy and Buildings* 37, pp. 972-981.

[9] Černe B., Medved S. (2007) Determination of transient two – dimensional heat transfer in ventilated lightweight low sloped roof using Fourier series, *Building and Environment* 42, pp. 2279 – 2288.

[10] Černe B., Medved S. (2005) Performance of thermally activated lightweight building element with two forced ventilated cavities; *CISBAT 2005*, Lausanne, Switzerland.

[11] PHOENICS 3.6.1; (2006) Parabolic, Hyperbolic or Elliptical Numerical Integration Code Series; CHAM, Wimbledon, Great Britain.

[12] Medved S., Arkar C., Leskovšek U. (2008) Heat response and energy efficiency of ventilated light weight building elements TRIMO, Faculty of Mechanical Engineering, Ljubljana.

[13] Medved S., Arkar C., Černe B. (2003) A large panel unglazed roof – integrated liquid solar collector – energy and economic evaluation, *Solar energy* 75, pp. 455-467.

[14] Vidrih B., Dolinar M., Medved S. (2006) The connection between the climate change model and a building's thermal response model: a case of Slovenia, *Journal of Mechanical Engineering* 52 (9), pp. 568-586.

[15] Wolfram Research. (2007) Mathematica 6.0, Champaign, Illinois, USA .